BILATERAL MANIPULANDUM TO SYNTHESIZE GROUND REFERENCED AND INTERLIMB VISCOELASTIC LOADS

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Abstract – **The bilateral system was designed to study limb stiffness in different movement tasks. The mechatronics consists of two angular voice coil actuators (± 40 Nm) with embedded rotary (± 20°) and torque sensors driven by voltage controlled current sources. DSP software routines to synthesize isotonic (preloads, stretches) as well as viscoelastic load schemes (Voigt model) were implemented for each sensor-actuator. The software further provides coupling of both sensor-actuators for interlimb loads as well as real-time video functions for experiment guidance. The system's performance was tested in forearm extensions against ground referenced and interlimb viscoelastic loads.**

***Keywords* – joint stiffness, bimanual contraction, interlimb dynamics, force feedback**

I. INTRODUCTION

Among other variables, limb stiffness is thought to play an important role for the control of posture and movement [1]. Limb stiffness reflects the myoactuator force to displacement relationship. Depending on the external load, limb stiffness is autonomously adjusted by such mechanisms as recruitment, co-contraction and reflex modulation so that load perturbations are damped out normally.

Viscoelastic loading alters the control and stability properties of a limb. For example if the stiffness of the load is locally higher than the myoactuator stiffness, an instability may occur. To study such myoactuator - load relationships, a manipulandum with software features to synthesize arbitrary isotonic and viscoelastic loads was developed. Bilateral systems to synthesize ground referenced loads are described in literature [2]. This paper describes the development of a bilateral system including a shared control scheme to synthesize also interlimb loads.

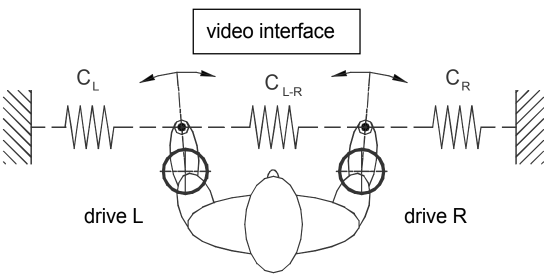

Fig. 1. Scheme of the bilateral manipulandum with ground referenced and interlimb spring loads

Both load types are shown by spring elements in Fig. 1. If we consider symmetrical extensions of both limbs, the interlimb load (C_{L-R}) may be set to the same value as the ground referenced series load (C_L + C_R). It then depends on kinesthetic and visual cues whether a difference in the load scheme is sensed during an extension. To exclude effects from direct limb vision, a video interface with real-time markers is needed for experiment guidance.

II. METHODOLOGY

A. Synthesis of a viscoelastic load

A linear viscoelastic load behavior is either described by a parallel (Voigt model) or a serial (Maxwell model) spring-damper arrangement [3]. Here the Voigt model with simple memory (spring zero position) is considered further. To synthesize this model behavior, the elastic and viscous force components are gained from the measured deflection $x(t)$, and translated to the user interface by a force actuator, see Fig. 2. Taking into account the mass m of the user interface, the system's differential equation (1) is given by:

$$f(t) = m \cdot \ddot{x}(t) + F_{Akt} = m \cdot \ddot{x}(t) + d \cdot \dot{x}(t) + c \cdot x(t) \qquad (1)$$

For angular motions, with J as interface inertia, the system's deflection response $\alpha(t)$ to torque loading $T(t)$ then is given as the complex compliance or admittance:

$$H(s) = \frac{\alpha(s)}{T(s)} = \frac{1}{J \cdot s^2 + D \cdot s + C} \qquad (2)$$

In this transfer function (2) the coefficient C is used to set the elastic component, and D to set the viscous component. For $D^2 < 4JC$ the interface inertia causes resonance oscillations f_{res}, such limiting the bandwidth of the viscoelastic synthesis:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{C}{J} - \frac{D^2}{4 \cdot J^2}} \qquad (3)$$

With an additional acceleration component in the feedback path the effect of the interface inertia may be reduced.

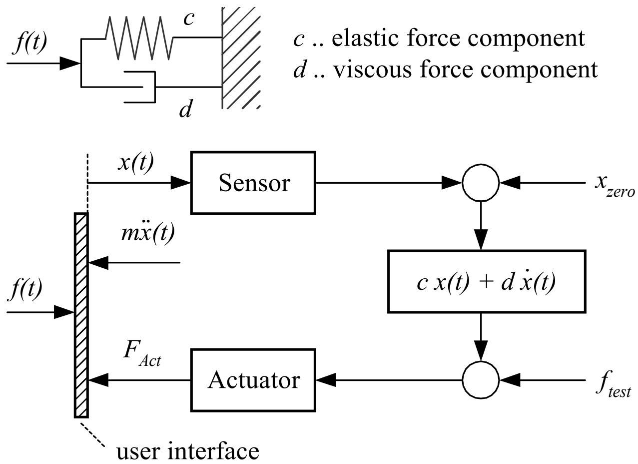

Fig. 2 Voigt model of viscoelasticity with hardware in the loop synthesis

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During bilateral operation, alternately ground referenced and interlimb loads have to synthesized. Basically an interlimb load behavior is achieved with a shared compliance controller. In such a controller the measured deflections of the left (α_L) and right (α_R) interface are reciprocally added to both controller inputs α_{Lc} and α_{Rc}. To switch from the ground referenced to the interlimb load scheme the matrix (4) was defined:

$$\begin{bmatrix}\alpha_{Lc}\\ \alpha_{Rc}\end{bmatrix}=\begin{bmatrix}1-k & k\\ k & 1-k\end{bmatrix}\cdot\begin{bmatrix}\alpha_L\\ \alpha_R\end{bmatrix}\quad with\ \langle k\,|\,0,0.5\rangle \qquad (4)$$

With k = 0.5 the both sensor-actuators become coupled to produce an interlimb viscoelastic load. The bi-limb torque output during anti-parallel deflections ($\alpha_L = \alpha_R$) is:

$$T_{LAkt}+T_{RAkt}=D(\dot{\alpha}_L+\dot{\alpha}_R)+C(\alpha_L+\alpha_R) \qquad (5)$$

During parallel deflections ($\alpha_L = -\alpha_R$) however, no bi-limb torque (6) is produced:

$$T_{LAkt}+T_{RAkt}=D(\dot{\alpha}_L-\dot{\alpha}_R)+C(\alpha_L-\alpha_R)=0 \qquad (6)$$

For k = 0, both actuators are controlled locally. During anti-parallel deflections the same bi-limb torque is produced as during coupled operation (5), however without interlimb force transmission.

B. Sensor-Actuator mechatronics

During experimentation with a manipulandum, the actuator superposes to the limb's myoactuation. The unforced actuator therefore has to follow the limb's motion without perceivable friction. To meet the limb's force generating capacity (about 40 Nm for the forearm), the actuator further must be powerfull. At least the actuator's inertia has to be kept small in order to avoid mass loading during operation (the limb inertia around the elbow joint is at about 0.06 kgm^2).

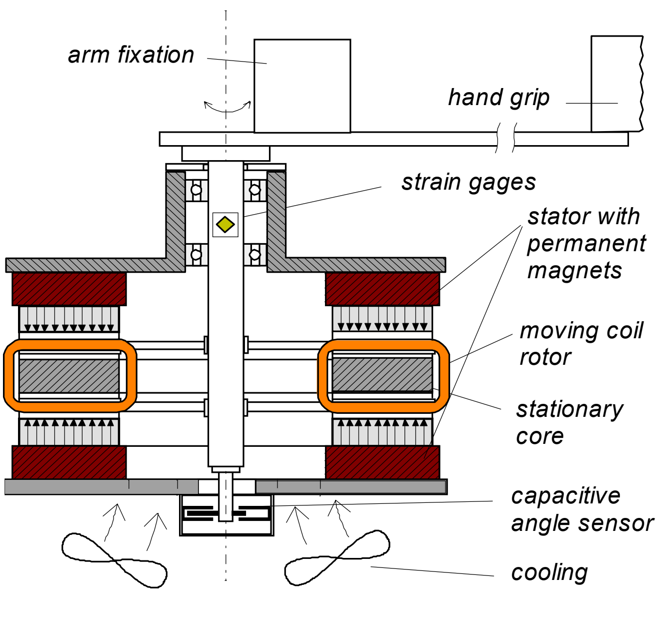

Fig.3. Electromechanical design of the rotary voice coil actuator with sensors and forearm fixation.

To meet these requirements a angular voice coil with ± 20° stroke range was chosen for actuation, see Fig. 4. The coil consists of a four pole assembly (∅ = 25 cm, R =1.22 Ω, L =4.9 mH) moving in a permanent magnetic stator field (BEI Inc, USA). The coil's motion is sensed by a precision capacitive angular sensor with a low mechano-electrical delay (Trans-Tec, Model 600, USA). Strain gauges are used for sensing the transmission torque between coil rotor (J_R = 0.0055 kgm^2) and forearm interface lever (J_L = 0.0083 kgm^2). The first mechanical resonance with blocked lever was found at 169 Hz. The actuator is powered by a voltage controlled current pump in order to avoid viscous friction from back-EMV. Torque output is specified linear up to 40 Nm, however cooling is necessary for higher levels (> 10 Nm). Coulomb friction from coil suspension (steel ball bearings) could be kept below 0.01Nm, resulting into a force dynamics of about 70 dB.

C. DSP control and visual interface

There are two control problems that have an influence on the systems performance. One problem is the coil and interface mass. This mass has to be considered as double integrator with a 180° phase delay for sinusoidal motion. If put into a digital feedback loop, with coefficient *C* as gain, the processing delay further increases the phase delay leading to self-excited mechanical. To avoid such resonance oscillations, which might be harmful to the user, a small viscous component *D* is always necessary.

The second problem arises from the differentiation to synthesize the viscous component. Differentiation amplifies the transducer's noise and if performed digitally, the processing delay further lags the differentiator's phase shift of 90°.

To reduce both problems, a small processing cycle would be advantageous. For technical control, a processing cycle of about 1/10 of the system's bandwidth is proposed [4]. Considering the bandwidth of human control, which is about 10 Hz, a processing cycle of 10 ms then seems to be enough. However, to achieve stable viscoelastic loads, up to values of *C* = 300 Nm/rad and *D* = 5 Nms/rad with the system components described above, a much smaller processing cycle of 1ms showed necessary.

The signal layout of the implemented DSP control scheme is given in Fig. 4. The main processing blocks are the signal mixing stage, the filter stage and the controller stage. Filters and controllers are realized by rational transfer functions. Additionally to viscoelastic loads, isotonic loads, stretches, and vibrations are needed for experimentation and identification of limb stiffness. Arbitrary function generators projecting to each output channel are used for their synthesis. Further function generators are used to modulate the signal paths and for set point control of the viscoelastic load. To generate angle dependent torque and viscoelastic load pattern, a content addressable memory was implemented further.

A floating point DSP-board, based on a TMS320C31-50 chip with galvanically isolated 16 bit AD/ DA front ends and a parallel interface for PC communication, was developed for process control of the two sensor-actuators, see Fig. 5. Within each process cycle (1kHz) bidirectional data transfers are performed between the DSP-board and the PC. The PC runs

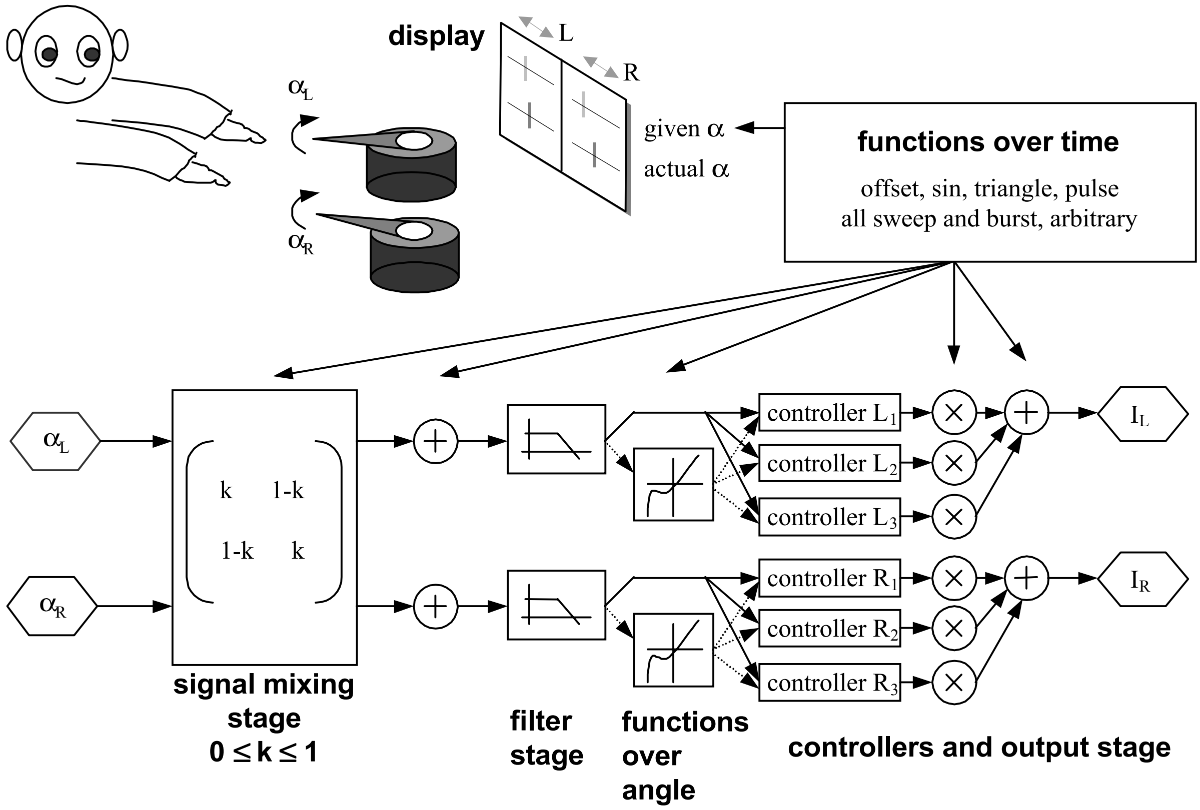

Fig. 4 Layout of the DSP control software

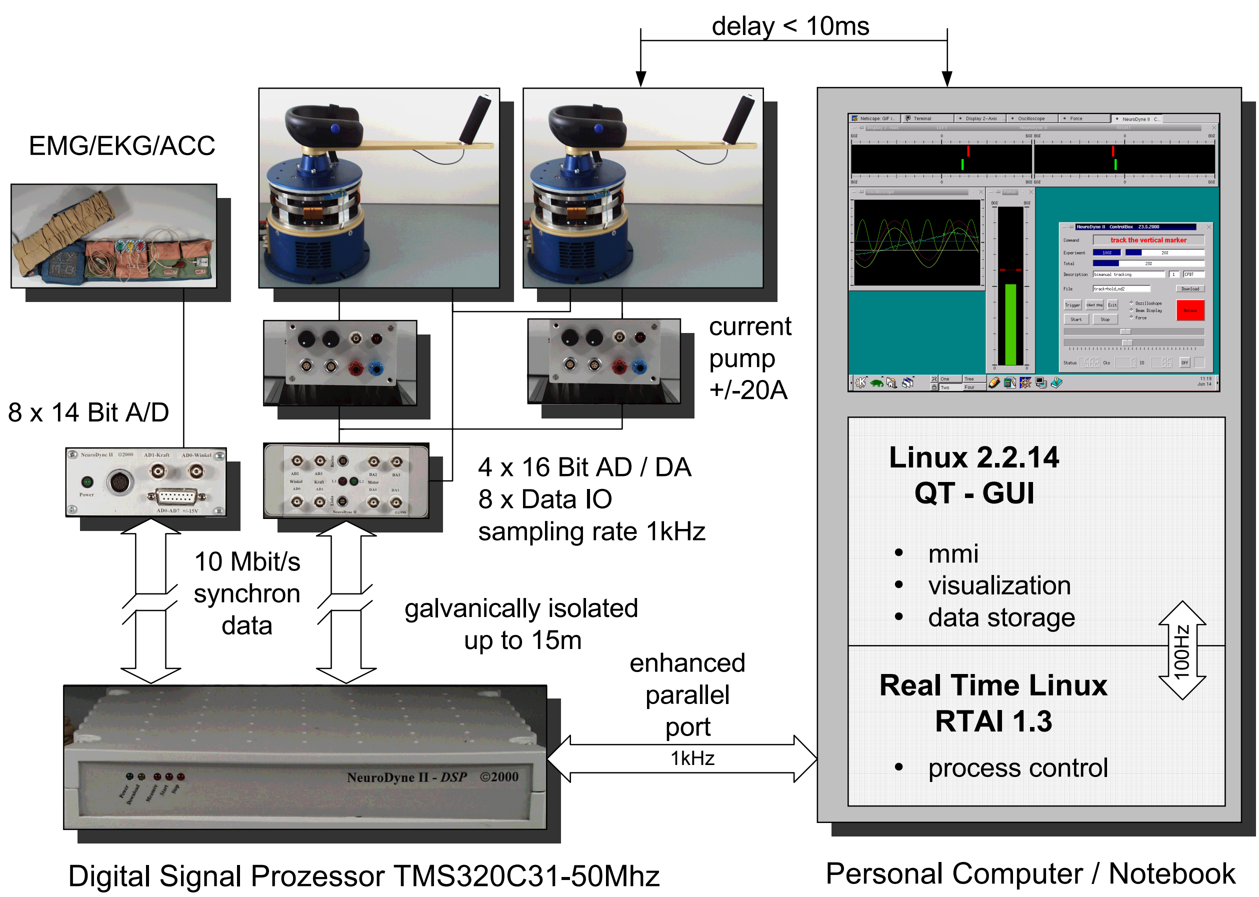

Fig. 5 System components of the bilateral manipulandum

under LINUX-RT at a process cycle of 10 ms. To avoid flickering of the realtime video markers, both the PC and the video cycle were synchronized to the DSP cycle. Horizontal and vertical markers (for synergistic limb movements) were implemented. In the left display field the scope for signal inspection, and in the right field the task sequencer for experiment guidance [5] is seen.

III. Evaluation

To evaluate the system's dynamics, the admittance magnitude of the unloaded interface lever was determined. As there was no force source available to excite the lever, a electrical test signal was used instead. The test signal (sinusoidal sweep) was superposed to current source, see input F_{test} in Fig. 2. Form the measured deflection response, two characteristica in the 0.2 to 50 Hz frequency band were determined, see Fig. 6. The dotted curves are simulated responses according to equation (2), however for sampled data (MATLAB control toolbox).

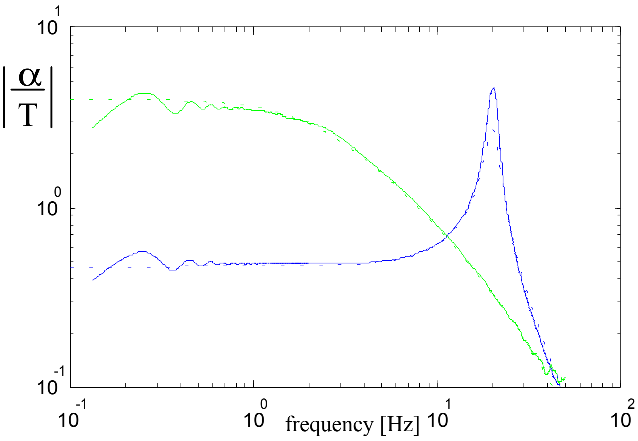

Fig. 6 Frequency responses of angular displacement to torque input
(- measured data, ... simulated data)

In the weakly damped response (C =200 Nm/rad, D =0.5 Nms/rad) the measured resonance peak is about 20% higher than in the simulated response, obviously due to hidden delays in the system hardware. In the second response (C =25 Nm/rad, D = 2.0 Nms/rad) a relative high correspondence is found over frequency.

To evaluate the system for physiological studies, bi-limb extensions against three elastic loads with same given torque level (10 Nm) were performed. The loads are: #1 ground referenced at low stiffness (k = 0, C = 100 Nm/rad), #2 ground referenced at high stiffness (k = 0, C = 250 Nm/rad) and #3 interlimb (k = 0.5, C = 250 Nm/rad). The viscous coefficient D was adjusted to critical damping.

The measured extensions are shown in Fig. 7. During #1 an almost stable equilibrium was maintained, indicating that the limb behaved stiffer than the load. In #2 both limbs fluctuate around their equilibrium, indicating that the load stiffness was higher now (although the limb's force generation capacity is not reached). As seen in the phase plot below, the fluctuations weakly correlate, indicating shared control in bi-limb postural tasks. In #3, during interlimb force transmission, both fluctuations became coupled.

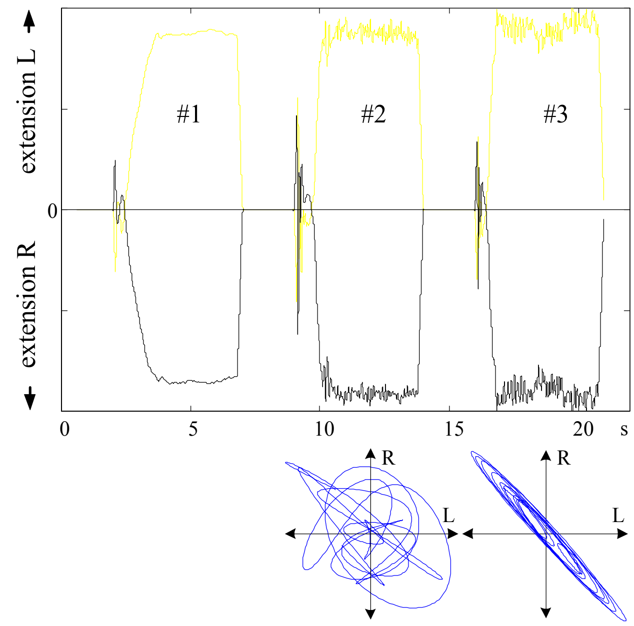

Fig. 7 Bilateral arm extension test. Upper plot: measured extensions versus time, lower plots: interlimb fluctuations (1-20 Hz) for the loads #2 and #3.

IV. Conclusion

A realtime controlled sensor-actuator system for viscoelastic load synthesis and interactive experimentation was described. By using voice coil direct drives for actuation, a high system dynamics at low mass loading was achieved. A special feature is the bilateral control mode, which allows to study bi- and interlimb sensory-motor functions. This bilateral manipulandum may also be used for clinical applications, to assess joint muscle tone [6], or for sensory-motor retraining of stroke patients.

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